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DEPOSITION OF DUST IN MINE GALLERIES

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by

G. Knight* and S.G. Hardcastle*

ABSTRACT

This report initially describes a simple theoretical treatment for particle loss when dust laden air is passed along a mine airway. Three cases are considered: particle loss by gravitational settlement, firstly, in laminar flow, and secondly in turbulent flow; and lastly, particle loss by diffusion in laminar flow.

For a typical mine gallery, 1000 m long and 6 x 3 m in cross-section with an airflow of 10 m^3/sec, the theory shows that:

1. few particles greater than 10 μm in size pass through;
2. that most of the dust in the respirable size range, 0.5 to 5 μm, passes through; and
3. diffusion loss to the walls is only significant for particles less than 0.01 μm in size.

Diffusion is of no importance for mineral dust, but may be important for diesel exhaust particulates and radon daughters.

The second part of this report reviews experimental studies into dust deposition in mine workings and their variance from theory. These studies suggest that deposition of the coarser fraction of the respirable dust is greater than expected.

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DÉPÔT DE POUSSIÈRE DANS LES GALERIES DE MINES

par

G. Knight* et S.G. Hardcastle*

RÉSUMÉ

Ce rapport décrit en premier lieu un simple traitement théorique de la perte de particules quand l'air chargée de poussière circule à travers la voie d'aérage d'une mine. On a examiné trois cas: la perte de particules par dépôt gravitationnel, d'abord par écoulement laminaire et ensuite par écoulement tubulaire et enfin la perte de particules par diffusion dans l'écoulement laminaire.

Dans le cas d'une galerie de mine caractéristique, mesurant 1000 m de long avec une section de 6 x 3 m et un débit d'air de 10 m^3/sec, les calculs théoriques ont produit les données suivantes:

1. très peu de particules dont la taille dépasse 10 µm passe à travers la voie d'aérage;
2. la majeure partie de la poussière qui est de taille respirable, soit de 0,5 à 5 µm passe aussi à travers la voie d'aérage; et
3. la perte aux parois par diffusion est remarquable seulement pour les particules dont la taille est inférieure à 0,01 µm.

La diffusion est sans importance dans le cas de la poussière minérale, mais pourrait en avoir pour les particules d'émissions de moteurs diesel et de produits de filiation du radon.

La deuxième partie de ce rapport présente une révision des études expérimentales sur les dépôts de poussière dans l'exploitation minière ainsi que les différences entre ces études et la théorie. Ces études suggèrent de plus que la quantité de fractions grossières de poussière respirable déposée est plus importante que l'on ne l'avait prévue.

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INTRODUCTION

A brief theoretical treatment of dust deposition in mine roadways is presented; this is compared with available experimental data for deposition. The report outlines the parameters which should be considered in a mine ventilation-environmental model to simulate dust behaviour in major airways.

A brief treatment of losses due to diffusion is given.

Departures from conditions amenable to theoretical calculations, but contributing to experimental results, are discussed.

The size distribution of airborne dust in mines has been described in previous reports (1,2).

The experimental studies which may aid the development of an environmental model have been previously reported (3).

GRAVITATIONAL SETTLEMENT

Fuchs has considered theoretical deposition in rectangular channels under the action of gravity and gives the equation:

$$\xi = V_s L / 2hU \qquad \text{Eq 1}$$

where, ξ is the precipitation efficiency

V_s is the settling velocity

L is the length

h is the height of the channel

U is the mean air velocity

The important conclusion was reached that the precipitation efficiency does not depend on the velocity distribution in the vertical plane of the channel (4).

However, in mine roadways the airflow is usually turbulent and it can be assumed that the particles, at least those below 10 μm in size, will be

stirred up and present in equal concentrations over the entire cross-section. The particles present at the edge of the boundary layer above the floor will settle into the layer and onto the floor at a rate proportional to their settling velocity. For concentrations under turbulent flow in circular ducts, Fuchs gives the equation:

$$C = C_o \exp [- 2 V_s L/\pi RU] \qquad \text{Eq 2}$$

where, C_o is the initial concentration

C is the final concentration

R is the radius of duct.

In a rectangular duct this can be approximately given as:

$$C = C_o \exp [- V_s L/hU] \qquad \text{Eq 3}$$

In mine roadways the cross-sectional areas are often irregular. The substitution is:

$$Q/A = Ubh/L.b = Uh/L \qquad \text{Eq 4}$$

where, Q is the volume of air flow

A is the total floor area of the roadway (horizontal projection)

b is the width of the roadway.

This simplifies the description of mine roadways and leads to the simpler equations for 1) and 2) above as:

$$\xi = \frac{V_s}{2} \cdot \frac{A}{Q} \qquad \text{laminar flow} \qquad \text{Eq 5}$$

$$(1 - \xi) = \exp \left[- \frac{V_s}{2} \frac{A}{Q} \right] \qquad \text{turbulent flow} \qquad \text{Eq 6}$$

The terminal falling velocity of particles can be determined from Stoke's Law with various corrections. The falling velocity under gravity of particles is tabulated in Appendix A.

From Equations 5 and 6, with the falling velocities given in Appendix A, the expected settlement in two model mine airways can be calculated. These are shown in Table 1.

Table 1 - Gravitational settlement losses

Particle Aerodynamic Diameter μm	Fractional Particle Loss to Floor from Settlement Roadway 1, A/Q=600		Roadway 2, A/Q=15	
	Laminar	Turbulent	Laminar	Turbulent
1	0.01	0.01	0.0003	0.0003
2	0.04	0.04	0.001	0.001
5	0.24	0.21	0.006	0.006
10	0.69	0.6	0.02	0.02
15	1	0.9	0.05	0.05
20	1	0.97	0.1	0.1
50	1	1	0.5	0.4
100	1	1	1	0.85

* Roadway 1 - 3 x 6 m cross-section, 1,000 m long, 10 m^3/sec airflow $\frac{A}{Q}$ = 600

Roadway 2 - 2 x 3 m cross-section, 100 m long, 20 m^3/sec airflow $\frac{A}{Q}$ = 15.

It can be seen that in the common type of airway, those with an area to flow ratio of about 600, that most of the coarse dust is deposited, whereas most of the respirable dust remains suspended and can penetrate other parts of the ventilation system. Where high velocity airways exist, there can be substantial penetration by coarse dust beyond those airways.

The main difference between laminar and turbulent airflows can be seen to be the increased penetration by coarser dust. However, this theoretical conclusion probably does not hold true in practice because of:

1. Incomplete mixing of coarse particles. The concentration is higher near the floor and the loss greater than calculated.
2. Inertial deposition of large particles on the irregular surfaces and structures in the airway.

DIFFUSIONAL DEPOSITION OF PARTICLES

Particles diffuse through gases and liquids under the random influence of Brownian motion. The exact solution of particle deposition is difficult and has only been obtained for simple cases. The expressions are complex. Fuchs equates and tabulates values for circular tubes and flat rectangular channels with laminar airflow in terms of a dimensionless constant, μ, (4).

$$\mu = DL/R^2U \quad \text{for a circular duct} \qquad \text{Eq 7}$$

and, $$\mu = DL/h^2U \quad \text{for a thin wide rectangular duct} \qquad \text{Eq 8}$$

By substituting $$Q = Ux \text{ cross-section} \qquad \text{Eq 9}$$

$$= \pi R^2U \quad \text{for circular duct} \qquad \text{Eq 10}$$

$$= hbU \quad \text{for rectangular duct} \qquad \text{Eq 11}$$

we obtain, $$\mu = \pi.D(L/Q) \qquad \text{Eq 12}$$

$$\mu = D(L/Q).(b/h) \qquad \text{Eq 13}$$

and by applying the aspect ratio to Equation 12:

$$\mu = \pi D(L/Q).(b/h) \qquad \text{Eq 14}$$

It can be seen that in the first case the fractional deposition is dependent only on the ratio of the length of the duct to the airflow. In the second case it also increases with the aspect ratio of the cross-section (b/h).

For the two roadways considered in Table 1, L/Q is 100 and 5, with aspect ratios of 2 and 1.5, respectively.

Table 2 shows the calculated losses due to diffusion using the three Equations, 12, 13, 14, with the diffusion losses given in Appendix B.

These three approaches show differences of up to an order of magnitude. It is clear, however, that diffusion losses to the walls of the chamber only become significant for very fine particles. It is probably true that, for these finer sizes, coagulation is also important leading to large decreases in the number concentration.

THEORETICAL DISCUSSION

The theoretical calculations made in this report ignore several factors normally present in mine airways, such as: wall roughness, structures, loose rock, etc. These factors are likely to increase particle deposition; this is supported by the experimental studies in the following section.

In the normal mine situation the results suggest that one can expect that coarse dust will settle close to the source and that respirable dust will penetrate most airways completely. The only possible significant loss of respirable dust could occur in very long airways and this may be of value in evaporite mines.

Diffusion and coagulation are probably completely insignificant for mineral dust behaviour. Coagulation of particulate in the concentrated diesel engine exhaust is probably significant in modifying the particle size distribution released to the atmosphere. Diffusional deposition on walls and coagulation are probably significant in the behaviour of radon daughters.

Table 2 - Diffusion losses

Particle Size μm	Fractional Loss to Walls from Diffusion					
	Roadway 1 L/Q = 100 B/h = 2			Roadway 2 L/Q = 5 B/h = 1.5		
	Eq: 12	14	13	12	14	13
0.1	-[1]	-	-	-	-	-
0.01	.001	.003	.0002	-	-	-
0.001	.03	.07	.015	.004	.006	.0005
0.0001	.55	.95	.31	.09	.12	.03

Note[1]: Diffusion losses are negligible for particle size above 0.01 μm.

DISCUSSION OF EXPERIMENTAL STUDIES INTO DUST DEPOSITION

Air velocity and roadway geometry are prime factors in controlling gravitational dust deposition in mines, and hence resultant dust concentrations. However, other factors include turbulence from obstructions and bends, constrictions and expansions, and changes in airflow direction; these are neither diffusional or gravitational, but predominantly inertial deposition mechanisms.

Two selected studies are discussed which demonstrate deposition in roadways and through a widely variable cross-section air course, namely a coal face. The studies were performed by Ford (5) and Reinhardt (6) in coal mines. The results of the studies, though not directly applicable to metalliferous mines, demonstrate deposition.

Results of deposition investigations in return roadways are shown in Fig. 1. The quoted deposition/change of concentration is for newly airborne dust, relative to an initial measuring point.

Both sets of results show significant deposition over 100 L/d_h, (≈300 m); where L is length and d_h hydraulic diameter:

Respirable Dust - Reinhardt 35-50% ($\bar{v}$ = 1.16 m/s)

Ford 50% ($\bar{v}$ = 0.95 m/s)

Coarse Dust - Reinhardt 60-90% ($\bar{v}$ = 1.16 m/s).

Beyond this distance the losses are less dramatic. The average velocity, $\bar{v}$, of each investigation is also given above.

Comparing these with the two theoretical airways:

1. Roadway 1 has L/d_h = 250, and v = 0.55 m/s. By Ford's curve this roadway would lose 62% of its respirable dust. Gravitational settlement is only 21-24% at 5 μm.
2. Roadway 2 has L/d_h = 42, v = 3.3 m/s, according to Ford, respirable dust

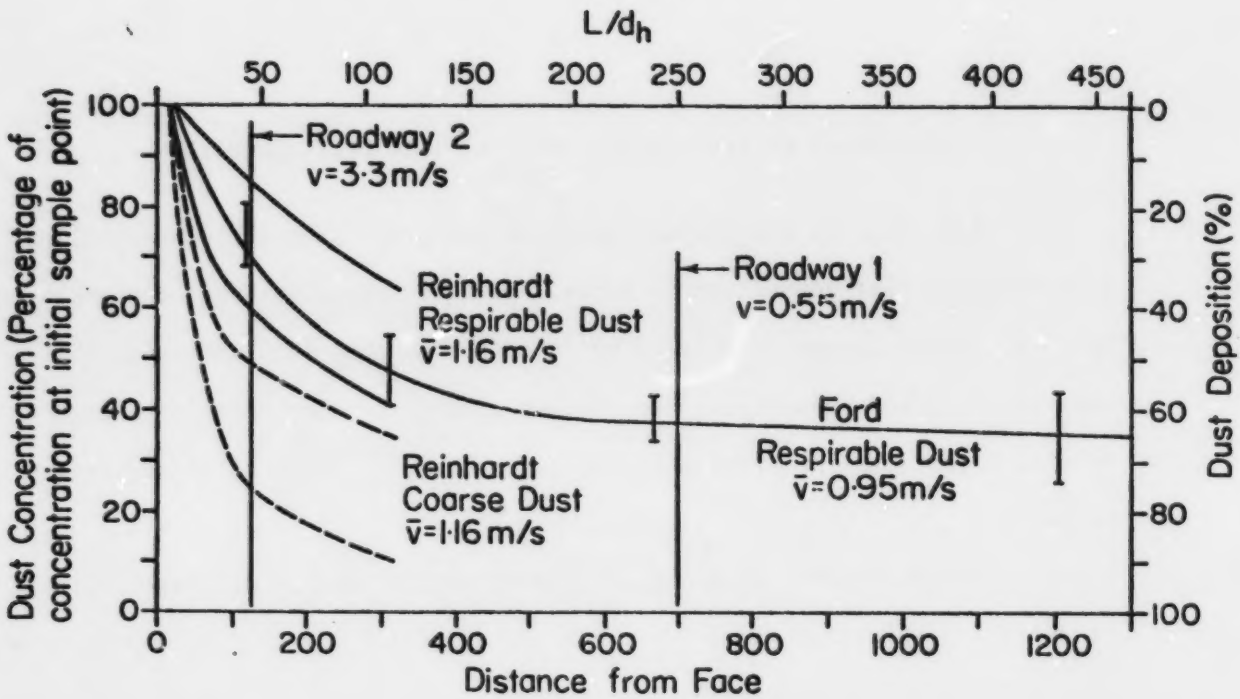

Fig. 1 - The percentage fall in dust concentrations along a return roadway.

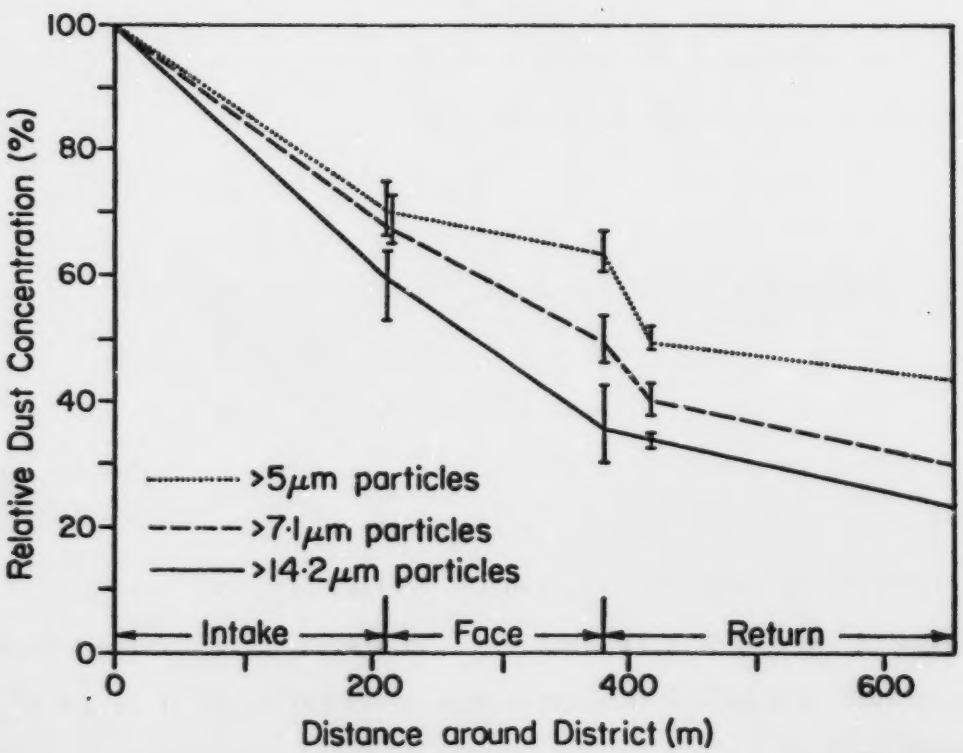

Fig. 2 - Deposition of various size fractions of stone dust through a district.

deposition should be 31%, and by Reinhardt ≈ 63% coarse dust deposition. Gravitational settlement only predicts 10% deposition at 20 μm.

Notably, there is a great difference between theory and observation that is not only due to the different velocities.

The effects of obstructions, bends, and constrictions in an airstream, and the resultant effect on dust is well demonstrated by Ford (5) in investigations of deposition around a coal face district. This is shown in Fig. 2. The results were obtained with tracer dust of three differing sizes to see the selective, or size-dependent, deposition.

As expected, the Figure shows that the larger the dust the greater the deposition, through the whole district there is a ≈20% difference between 5 μm and 14 μm particles. Also evident for the finer dusts is a rapid deposition directly following an airflow expansion such as with the cross-sectional change from the face to the return airway.

Both quoted studies adequately show dust deposition that occurs in mines, can be substantial if the dust is newly airborne or subject to a rapid change of airflow parameter. Where the airborne dust is old, ≈200 L/d_h after its source, or not rejuvenated, little further deposition will occur, which limits deposition to 60% of the initial concentration of respirable dust.

In metal mines, as in coal mines, it is difficult to measure the true concentration of dust near a source. Generally, for sampling purposes, a consistent downstream distance equivalent to 10 roadway diameters is suggested to obtain a representative and turbulent mixed cloud. Even this cloud ≈30 m from the source has been subject to deposition. This recommended distance of consistent roadway, no obstructions or junctions, from a single source may be difficult to obtain in metal mines. Therefore, sources may have to be generalized together and samples taken at greater distance from sources.

Depending on source and age of the dust at the initial measuring

point, lower deposition values can be expected. This may achieve a maximum of 40% and some selective account for this should be considered in a mine environmental simulation model.

A simple model of dust deposition has already been developed for recirculatory ventilation systems (7,8).

Another major dust deposition phenomenon which has been found to occur is in ascending airways. In these, adiabatic expansion can lead to condensation of the moisture in the air. The condensation can occur on dust particles. The resultant water drops, 'rain',fall through the air collecting more dust and settle onto the floor. The deposition of dust appears to have been almost total in a return airway with a 300 m rise above the point that condensation started.

CONCLUSIONS

In a ventilation-environmental simulation model it is concluded that:

1. For many airways, as a first order approximation it can be considered that respirable dust passes through them without significant loss.
2. Only in very long airways is there a significant loss of respirable dust. That is those with floor area to airflow ratios >1000 s.m.
3. In the immediate locality of dust sources, deposition will need to be included. This is unless they are measured once turbulent mixing and deposition equilibrium are obtained with distance.
4. Coarse dust can be ignored in the computer model, i.e., >10 μm because it is only transported short distances and is not well mixed with the air.

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APPENDIX A - PROPERTIES OF PARTICULATES

These corrected sedimentation velocities and diffusion coefficients have been abstracted from a published table*. All values refer to unit density spheres of the given particle diameter. The aerodynamic diameter of a particle is the diameter of a unit density sphere with the same falling velocity in air.

* Billings and Gussman, "Tables for Aerosol Physics", Billings and Gussman, Waltham, Mass; 1971.

Table A-1 - Selected properties of particles in air

Particle Diameter μm	Corrected Sedimentation Velocity m/sec	Corrected Diffusion Coefficient m^2/sec
0.001	6.533×10^{-9}	5.11×10^{-6}
0.002	1.31×10^{-8}	1.28×10^{-6}
0.005	3.30×10^{-8}	2.06×10^{-7}
0.01	6.69×10^{-8}	5.23×10^{-8}
0.02	1.37×10^{-7}	1.34×10^{-8}
0.05	3.74×10^{-7}	2.34×10^{-9}
0.1	8.63×10^{-7}	6.75×10^{-10}
0.2	2.25×10^{-6}	2.20×10^{-10}
0.5	1.00×10^{-5}	6.26×10^{-11}
1	3.51×10^{-5}	2.74×10^{-11}
2	1.30×10^{-4}	1.27×10^{-11}
5	7.77×10^{-4}	4.86×10^{-12}
10	3.06×10^{-3}	2.39×10^{-12}
20	1.21×10^{-2}	1.18×10^{-12}
50	7.31×10^{-2}	4.72×10^{-13}
100	2.48×10^{-1}	2.35×10^{-13}

APPENDIX B - DIFFUSION

Fuchs gives a number of tables relating wall loss by diffusion to a dimensionless group combined to μ. The tables given below have been abstracted from the values given by Fuch's equation 39.3 for laminar flow in a circular tube and by equation 39.7 for laminar flow in a rectangular duct of high aspect ratio. These tables relate the dimensionless group, μ, to the deposition loss in the duct.

Table B-1 - Diffusion losses in ducts - laminar flow

Dimensionless Group μ	Fractional Loss to Walls Circular Duct	Rectangular Duct
0.00001	0.0012	0.0001
0.00002	0.0019	0.0002
0.00005	0.0034	0.0003
0.0001	0.0055	0.0005
0.0002	0.0085	0.001
0.0005	0.016	0.003
0.001	0.024	0.006
0.002	0.038	0.013
0.005	0.07	0.03
0.01	0.11	0.05
0.02	0.16	0.08
0.05	0.28	0.15
0.1	0.42	0.24
0.2	0.62	0.37
0.5	0.94	0.64
1	-	0.86